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Mechanical characterization of mortars used in the restoration of historical buildings: an operative atlas for maintenance and conservation

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Abstract. The complexity of the architectural and structural restoration of historical buildings requires a careful choice in the use of repair mortars compatible with the original materials of the existing building. It is important to set up an atlas of reference, compared to many mixtures of mortars and conglomerates, useful to support the operational choices in the project of restoration, recovery, and maintenance of historical buildings. The aim is also to encourage the use of local materials with a "short supply chain", compatible with buildings and applied by traditional techniques. The research makes use of experimental bending, compression and elastic modulus tests on different mixtures of mortars. This paper describes some of the first results obtained so far, because the research is still underway for many different mixtures to test and catalogue. The comparison between the data and the reference values that will be identified, will lead to set up a reference atlas of mechanical behaviour of repair mortars in order to direct the design and operational choices in function of requirements and performance (of the wall systems) of each specific cases in the field of the restoration of historical buildings.

1. Introduction

The choice of materials represents a fundamental part to correctly direct a repair work of historical buildings, ensuring their conservation over time. The choice is therefore subject to the verification of the compatibility from the aesthetic / historical point of view (figure 1a) and the compatibility from the physical-mechanical and chemical point of view (figure 1b). In the specific case, the mortars used in the historical buildings (but also in the new buildings), often need of replenishment or a total replacement of materials (of wall joints, or external plasters, e.g.), due to the natural degradation during the time or to an extraordinary event (such as an earthquake). Often many restoration work proved to be ineffective shortly (detachment of repair mortars) due to evident chemical-physical-mechanical incompatibility in comparison to the masonry support (figure 1b) [1, 2]. The interface surface between plaster and masonry is the site of mechanical or thermo-hygrometric strains, due to thermal variations, rising damp [3, 4] or seismic forces. To mitigate these strains it is essential that the repair mortar has similar physical-mechanical characteristics to those of the historical repaired plaster and of the historical masonry. At the Department of Structural Geotechnical Building Engineering (DISEG) of the Politecnico di Torino, several experiments were carried out by fatigue and thermo-hygrometric stresses tests for validating the most durable repair mortar compatible with a specific historical masonry [1-5]. The experimental prequalification phase proved to be very useful for the choice of the most compatible material in important restoration sites [2, 6].

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Figure 1. (a) Patches of cement/lime based plaster on historic façade; (b) deterioration (with detachment) of cement plaster applied for the restoration of a masonry subject to moisture.

In this research, the mechanical characteristics are evaluated (dynamic elastic modulus, bending and compressive strength) of certain formulations of mortars produced and tested at the Mortars Laboratory of the DISEG Department (Politecnico di Torino), thus trying to investigate the choice from the side of mechanical compatibility with existing walls. The research is in progress [7] and in this paper the first results will be presented. The goal is indeed to provide useful data to help draft an atlas as a tool for assessing the behaviour and compatibility of repair mortar for the building heritage and therefore can be a useful tool for the operators (designers, Superintendences and workforce) in the decision-making process for the planned intervention. The research is part of an international scientific debate sensitive to the characterization of mortars within restoration building sites [8-10].

2. Types and composition of mortars

The mortar is a conglomerate composed of a mixture of water, sand, binder and any additives. Dosing appropriately, a mixture is formed with behaviour plastic, which through irreversible chemical reactions hardens over time. It is also important to highlight the differences between mortars, pastes, plasters and concretes, which although similar in various aspects differ in the composition (table 1).

Table 1. Types and composition of mortars.

Pastes	Plasters	Mortars	Concretes
Water	Water	Water	Water
Binders	Binders	Binders	Binder (cement or *pozzolana*)
Any additives	Fine aggregates (max 0.5 mm)	Aggregates (max 4 mm)	Sand (max 4 mm)
	Any additives	Any additives	Gravel (max 8 mm)
	Adjuvants	Adjuvants	Medium gravel (max 65 mm)
			Any additives

Thanks to technological progress it was possible to produce mortars with specific compositions, expanding the field of application of the mortars:

– *Mortars for restoration*: of monuments, are generally mortars special with *ad hoc* formulations, which vary case by case. Once hardened, the mortar must have similar characteristics compatible with those of the material on which is applied. These mortars must be carefully evaluated for the following properties (after diagnostic campaign): elastic modulus, compressive strength, flexural strength, expansion coefficient, porosity and permeability.

– *Mortars for renovation*: to deny water penetration through underground and above-ground walls, used in tanks, ducts, sewers, foundations, canals, tunnels, ducts, dams, for leaks and for filling cavities. Characterised by a rapid hardening and a high and immediate mechanical strength.

– *Strengthening mortars:* as part of the repair mortars for strengthening work are used to fill failures or macro-porosity and to perform anchors by fixing. Among these mortars is the so-called strengthening grout, which does not it is nothing but an expansive mortar. The grout is used to fill the cavities of the masonry by pouring or even by injection.

– *Mortars for recovery:* the recovery work consists in repairing a structure. High-strength chemical and mechanical synthetic mortars are used, because must be able to withstand stress challenging. In these particular mortars it is common to find thin fibers added, for example glass fibers or polyamide fibers, which are used to create a widespread "reinforce". This category also includes mortars used to reconstruct the cover of a work in reinforced concrete.

– *Mortars for masonry:* this type of mortar is linked to the construction of brick or stone walls, and is used to ensure the correct installation and binding of the masonry elements. For this use almost all types of mortar can be used, however the compatibility with the mechanical characteristics of the support is fundamental (enough, with diagnostic support).

– *Mortars for finishing work:* all those mortars that are used for various uses, as the creation of a shaving layer filler on a surface, so to allow the application of coatings and painting, can therefore be considered as an adhesive bridge for subsequent plastering. They are also used for gluing non-structural elements such as insulating tiles or panels or for sealing joints or joints.

Since the mortars of the conglomerates consist of a mixture of various elements, depending on the composition of this mixture we can distinguish various types of mortars:

– *Aerial mortars:* formed by water, sand and an aerial binder as lime aerial (powder or putty lime). The main feature of these mortars is that they can only harden on contact with the air. They therefore serve for plasters and walls in elevation stressed in a manner reduced and exposed to the air.

– *Hydraulic mortars*: with hydraulic properties, or able to harden even in contact with water, therefore suitable for work in damp and cold environments. They are composed of water, sand and natural hydraulic lime or of hydrated lime in powder (aerial) with the addition of aggregates with pozzolanic properties of natural origin (e.g. *pozzolana*) or artificial (e.g. *cocciopesto* or kaolin).

– *Cement mortars*: with cement as a binder. Strength development (mechanical and chemical) is rapid, waterproof and they have a remarkable duration.

– *Compound or bastard mortars:* consist of a mixture of two or more different types of binders. E.g. cement is added to an air lime mortar to give superior mechanical strength, or a cement mortar is added with lime aerial to improve its workability. Lime combined with gypsum guarantees a quick setting.

3. Mortar production in laboratory test and experimental results

The mortars made belong to different types: aerial, hydraulic, cement and bastard mortars. The cement used is of the type 32,5 and 42,5 R. The aerial lime corresponded to *"Calce del Brenta"*, a special magnesic putty lime more than three years aged. Siliceous sand was extracted from the seabed of the tertiary basin of the Po Valley, wet washed in a cyclone at the quarry. The first type of *cocciopesto* corresponded to a Trass of natural origin, ground into very fine powder, without chemical additives, free of cement. The second type was a reactive aggregate obtained from crushed tiles and bricks without clinkerization, only aggregate less than 150 μm were used. The natural raw pearlite, a variety of volcanic rock effusive, was with medium grain size (0.3-1.2 mm) and coarse grain size (0.8-2.5 mm), non-toxic, inert, non-combustible. The mortar specimens were prepared in a non-conditioned laboratory environment with a temperature of approximately 20 +-2 °C and U.R. 60:70%. For each of the formulations made, 9 specimens were produced standardized (40x40x160) mm, of which only 3 will be broken. The remaining 6 specimens will become part of the DISEG laboratory archive in order to allow possible future comparisons or checks. The mortars were coded by the letters G, H, I , L, M, N, O and P (table 2).

Table 2. Mortars compositions.

		MORTAR COMPOSITIONS								
		AGGREGATES				BINDERS				
						AERIAL LIME		HYDRAULIC LIME		
		SILICEOUS SAND OF QUARRY	COCCIOPESTO	POZZOLANA	PERLITE	LIME PUTTY	HYDRATED LIME IN POWDER	HYDRAULIC LIME (NHL 3,5)	CEMENT PORTLAND (32,5)	CEMENT PORTLAND (42,5)
SAND MORTAR AND HYDRAULIC LIME	G1	3						1		
	G2	2.5						1		
	G3	12				1		3		
SAND MORTAR AND CEMENT PORTLAND (32,5)	H1	3							1	
	H2	12				2			2	
	H3	12				1			3	
	H4	12				3			1	
SAND MORTAR AND CEMENT PORTLAND (42,5)	H5	3								1
	H6	12				2				2
	H7	12				1				3
	H8	12				3				1
SAND MORTAR AND COCCIOPESTO	I1	3	100% fine			1				
SAND MORTAR AND PERLITE	L1	3			100% fine	1				
	L2	2			100% fine	1				
SAND MORTAR AND HYDRATED LIME IN POWDER	M1	2.5					1			
	M2	3					1			
	M3	3.5					1			
SAND MORTAR AND LIME PUTTY	N1	2.5				1				
	N2	3				1				
SAND MORTAR + COCCIOPESTO + HYDRAULIC LIME IN POWDER	O1	2.5	60%				1			
	O2	3	60%				1			
SAND MORTAR + POZZOLANA + HYDRAULIC LIME IN POWDER	P1	2.5		30%			1			
	P2	3		30%			1			

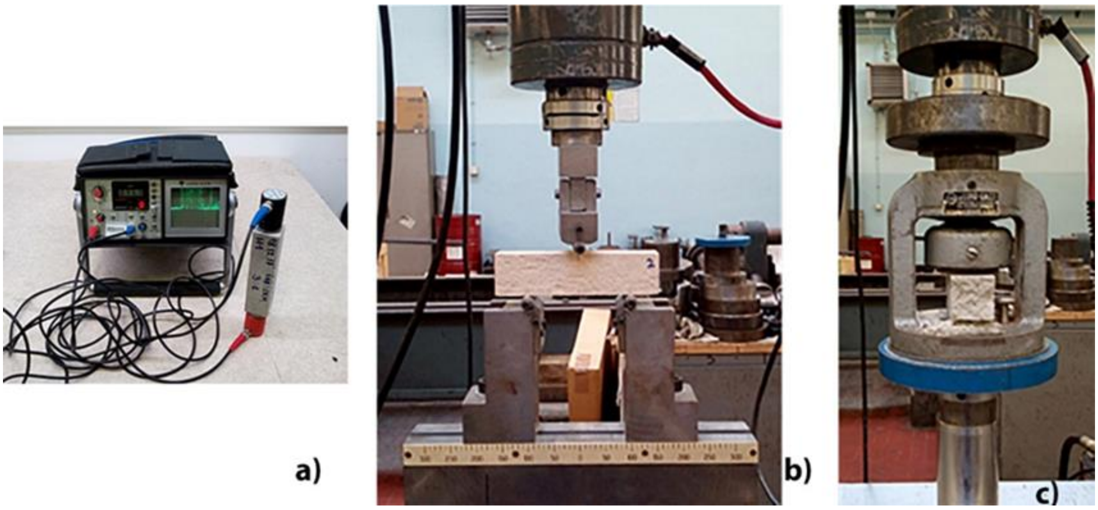

Figure 2. (a) ultrasonic test; (b) bending test; (c) compression test on mortar specimens.

The main measurement performed in the experimentation concerned the determination of the elastic modulus of different mortar formulations by means of the ultrasonic test (figure 2a). The purpose of this non-destructive survey was to detect anomalies in the ultrasonic waves materials (cracks, porosity or cavities). Sound is an elastic mechanical vibration, produced by expansion and compression of the particles that make up a propagation medium. The ultrasonic are therefore sound waves (longitudinal) with a high frequency, beyond the audible threshold. Conventionally the ultrasounds range from the frequency of 20 kHz to 1 GHz. The time required for a wave to pass through a material was measured. If an ultrasonic wave encounters a vacuum layer or a material during its journey different, undergoes alterations. The ultrasonic test is described by the UNI EN 12504-4: 2005 standard [11]. The purpose of the test was to determine the propagation speed of the ultrasonic wave. This value will then be used to calculate the dynamic elastic modulus E_d by (1):

$$E_d = v_m^2 \cdot \rho_m \tag{1}$$

where v_m is the average propagation speed (m/s), ρ_m is the average density of the formulation (kg/m^3).

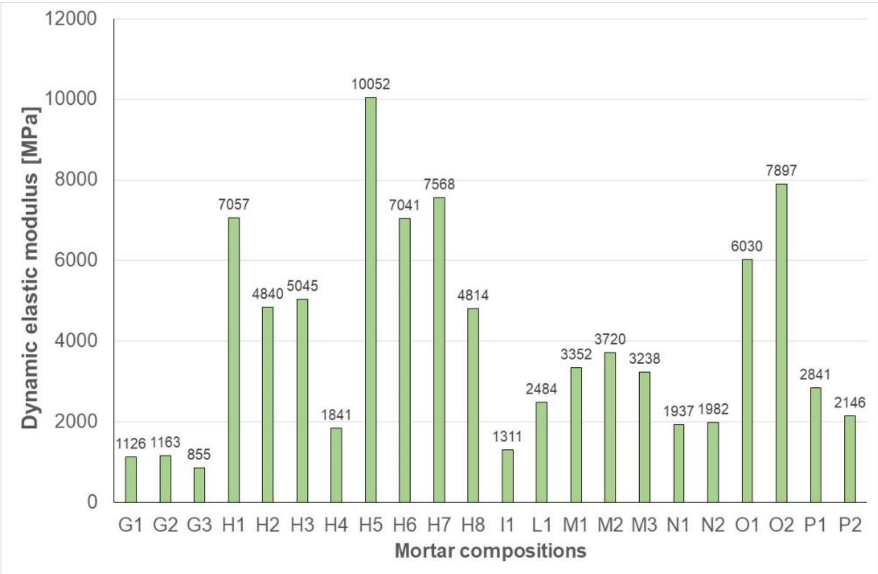

Figure 3. Medium values of dynamic elastic modulus for each mortar composition.

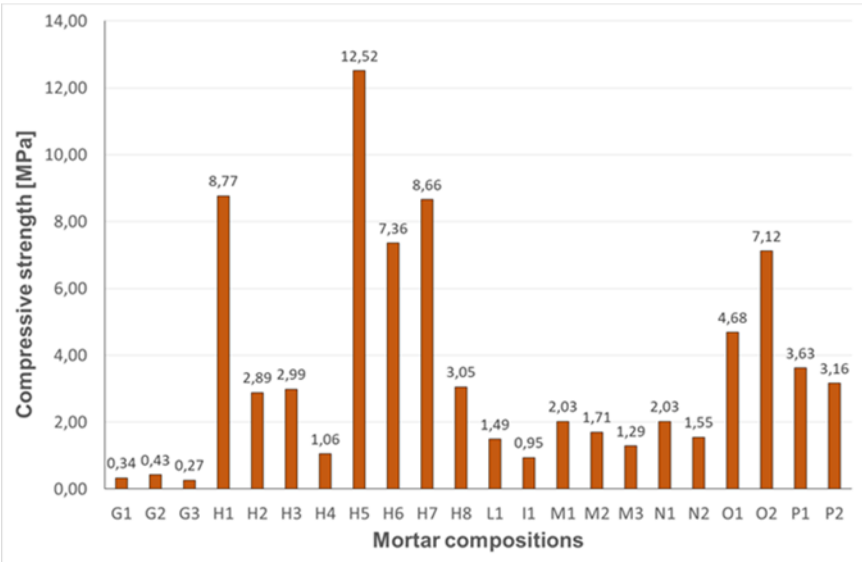

Figure 4. Medium values of compressive strength for each mortar composition.

Since the elastic modulus is directly proportional to the speed of transit of the pulses ultrasonic, higher speed formulations also have higher values of Ed. As can be seen in figure 3, the set of specimens that presented the average Ed value greater was made by cement or cement and lime putty (category H), with the exception of the specimens with a preponderant amount of lime putty compared to cement (H4 and H8). Among the category H, the greater Ed was obviously recorded by the specimens composed of 42.5 cement (H5, H6, H7, H8). Within category H cement specimens have returned very high values: it can be seen that as the lime / cement putty ratio increased, the value of Ed decreased. Also the category

O2, which was made with sand, *cocciopesto* and hydrated lime powder with 3:1 aggregate/binder ratio, shown a high Ed value. The high speed of this formulations corresponded to a reduced porosity of the specimens. While the absolute lowest values of Ed were recorded by the specimens made with hydraulic lime (category G). Also among the hydraulic lime mortars, the G3 mortar (which presented lime putty in its composition) had a lower elastic modulus compared to the other two mortars (G1 and G2) which had hydraulic lime as the binder. Comparing the values of the G1 and G2 mortars it was possible to see how the quantity of hydraulic lime increased the elastic modulus. The aggregate / binder ratio in fact affected the density of the specimens, which was directly proportional to Ed. The tests were performed with two different types of sonic probes (50 kHz and 120 kHz), finding results comparable.
For a comparison with the experimental results of the elastic modulus, the bending (figure 2b) and compressive (figure 2c) tests described by the UNI EN 1015-11:2007 standard [12] were also performed. The results of the compressive strength shown in figure 4 confirmed the similar trend already found by the measurement of the dynamic elastic modulus. A more rigid mortar corresponds to higher compressive strength values, and vice versa. The bending test was performed with 3 supports. For technical reasons the data of flexural tests on G-H-I-L mortars were not available, however the trend detected by the results of the remaining formulations confirmed the mechanical characteristics previously obtained (figure 5).

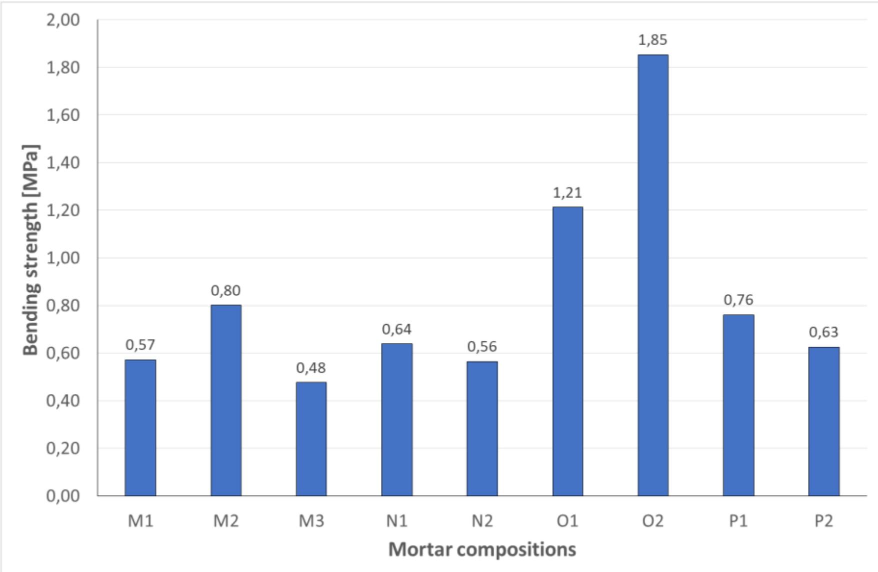

Figure 5. Medium values of bending strength for each mortar composition.

4. Discussion

The elastic modulus of the materials has a high importance especially in the presence of coupled materials such as e.g. in the case of a plaster applied to masonry support. The mortar, once applied, begins the phases of setting and hardening which inevitably lead to the emergence of controlled deformations and strains, which are only partially transmitted to the masonry. Thermal cycles, shrinkage due to plaster curing, etc., would not compromise the durability of the mortar if it were not bound to the rigid support. The case of plaster applied to the wall support, however, corresponds of a constraint, the displacements due to expansion or compression phenomena are prevented. As a result, strains arise in the material applied: the strains created in the material must balance that due to the constraint. The value is proportional to the elastic modulus of the material; therefore, the tensile or compressive stresses will be greater the greater the rigidity of the material itself. These are the reasons why the elastic modulus of materials is extremely important in the case of coupled materials. To avoid the degradation phenomena just described it is necessary that between the two materials (the new and the pre-existing) there is a certain mechanical compatibility and that the values of the elastic modules are compatible. This means that the elastic modulus of the plaster applied on an old masonry must be similar, better if inferior, to

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that of the support [2, 5]. In this way the stresses are borne by the wall, having greater stiffness. Mechanical compatibility is closely linked to the value of the elastic modulus as it is the parameter that best represents the strength and deformability of the material. The atlas under construction will contain the elastic modulus of the different mortar mixtures (the aim is carry out data for 100 mortar mixes) so that the designer can compare the values with those of the historical masonry on which will be applied.

5. Conclusions

The technical operators which take an interest in maintenance, conservation and restoration of the heritage architectural may need to analyse data that helps correct it formulation of a mortar. The premixed solutions on the market no longer contain the preparation methods and formulations that were once handed down from master to master. The formulations made for this paper seek to regain part of the knowledge that has been partially lost due to industrialization. Industrial mixtures will never have a perfect coincidence with mortars in place, perhaps not even full physical-mechanical compatibility. Therefore, those who work in the sector, following surveys on historic mortars in operation will have to formulate ad hoc compatible mixtures. These analyses (sometimes very expensive) are indicated for protected monuments and buildings. For widespread construction, clients and designers do not usually carry out diagnostic investigations. Have a reference text containing formulations and data to support the project and construction site can help technical operators.

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